

# Safeguarding Geological Repositories – R&D Contributions from the German Support Programme

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**Abstract.** Germany has contributed actively to R&D related to safeguarding geological repositories since 1980, first on the national level, since 1990 also through the SAGOR, SAGOR II and ASTOR group of experts, and other German Support Programme tasks. While earlier studies identified issues of essential relevance (aspects of retrievability, need for Design Information Verification (DIV), definition of physical boundaries) and developed safeguards approaches for geological repositories and encapsulation plants, R&D more recently has focused on technologies for safeguarding geological repositories. These are: i) Satellite imagery: In a joint task with the Support Programmes of Finland, Japan and Canada, the potential of synthetic aperture radar (SAR) data acquired by remote sensing satellites was demonstrated. ii) Geophysical methods: Measurement campaigns at the Gorleben exploratory mine showed the applicability of seismic and acoustic measurement methods to detect clandestine underground mining activities. Based on the results, a follow-up project has modelled the propagation of seismic waves from different sources in the salt and surrounding sediments. Another project has investigated the applicability of underground radar technology as a directive and wide ranging technology. Active radar systems could probably be used to set up a protective screen around a geological repository. iii) Autonomous navigation and localisation: The German Support Programme has recently started a feasibility study on simultaneous localisation and mapping (SLAM) systems for safeguards verification purposes. Results achieved during field tests have indicated several possibilities and challenges for using indoor navigation and mapping technologies in support of geological repositories safeguards. The paper presents the lessons learnt from the earlier studies and gives an overview of the results and implications of recent and on-going projects for safeguarding geological repositories.

## 1. Introduction

### 1.1. *Spent fuel management in Germany*

The current German policy on spent fuel (SF) management is mainly based on the German Atomic Energy Act (AtG) and its Amendments in 2002, 2010 and 2011 with regard to the phase-out of nuclear energy for commercial electricity production, and the Act governing the selection of a repository site for heat-generating radioactive waste (Standortauswahlgesetz, StandAG).

The provisions the 2002 Amendment to the AtG set the basis for the fundamental shift in the German energy policy under the coalition government of Social Democrats and the Green Party at that time, namely “to phase out the use of nuclear energy for the commercial generation of electricity in a structured manner, and to ensure on-going operation up until the date of discontinuation.”<sup>1</sup>. The coalition government of Christian Democrats and Liberals from 2009 decided to extend the operating lifetime of the 17 nuclear power plants (NPPs) in Germany for an average of 12 years (2010

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<sup>1</sup> AtG 2002, §1 (1)

Amendment to the AtG). However, following the Fukushima accident in March 2011, the same government decided to shut down eight NPPs units immediately and to again amend the AtG. The 2011 Amendment to the AtG, entering into force in August 2011, regulates the stepwise phase-out of nuclear power generation until the end of 2022 by defining the maximum electricity volume and latest end of operation for the remaining nine NPPs units.

Besides terminating the use of nuclear energy for electricity production, the 2002 Amendment to the AtG also established new waste management provisions. With effect of July 2005, the then option of delivering SF originating from German nuclear power plants for reprocessing became illegal<sup>2</sup> and direct disposal of SF the only concept. Furthermore, the operators of the German nuclear power plants were required to set up an interim storage facility on-site and to store the SF assemblies until their surrender to a facility for final disposal.

Accordingly, the German concept for SF management envisages the following steps: i) temporary storage of SF assemblies in cooling pools on-site; ii) loading of SF assemblies into CASTOR® casks after a cooling time of usually 5 years; iii) dry storage of CASTOR® casks in interim storage facilities on-site; iv) emplacement of SF assemblies and high-level radioactive waste (HLW) from reprocessing in the past in a deep geological repository.

For selecting the repository site, a new selection procedure starting with a blank map of Germany was laid down in the Repository Site Selection Act, which entered into force in July 2013. A commission has been set up to prepare the site selection procedure by the end of 2015; it consists of 33 members from academia and the various groups of society as well as the Federal Parliament and the Bundesrat (Federal Council). However, the decision on the major steps of the selection procedure lies with the German Bundestag, which will pass the respective acts. Moreover, the Federal Office for the Regulation of Nuclear Waste Management has been established as a new authority to ensure that the procedure for locating and selecting the repository is based on scientific principles and to realise the EU's principle of separation between operators and the regulatory authority. [1]

## ***1.2. German R&D activities for safeguarding geological repositories***

In 1979, a joint decision taken by the German Government and the Länder Governments initiated development activities towards direct final disposal of nuclear fuel including work related to a safeguards concept for a reference final repository for spent nuclear fuel in rock salt, taking into account existing safeguards techniques. From 1980 to 1988 safeguards development took place on a national basis only and addressed the definition of safeguards issues and development of approaches.

In 1988, an international consultants group convening at the IAEA recommended to link IAEA Safeguards on spent nuclear fuel to the staying in force of the NPT, which meant that also SF embedded in geological repositories should remain under IAEA Safeguards, as long as the Non Proliferation Treaty (NPT) would be valid. As a result, the IAEA agreed to establish a corresponding task under the German Support Programme. For a number of years, Germany was the only country addressing safeguards for direct final disposal of SF in cooperation with the IAEA. When also other countries started to address direct final disposal and related safeguards issues in the 1990's, the IAEA established a joint task dubbed SAGOR (Safeguards for the Final Disposal of Spent Fuel in Geological Repositories). At that time, a lot of issues had already been studied under the German Support Programme. The results had been made available to the IAEA. In the frame of SAGOR, the German Support Programme provided its results also to the Support Programmes cooperating under the SAGOR task, so that the German results could be taken into account. The follow-up joint task SAGOR II ended in 2005 and was succeeded by the ASTOR Expert Group (Application of Safeguards to Geological Repositories) with the German Support Programme as an active participant and is continuing so until today. Table I lists the German Support Programme Tasks on Conditioning and Final Disposal from 1988 until today.

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<sup>2</sup> AtG, §9a (1)

Table I. German Support Programme Tasks on Conditioning and Final Disposal

No.	Title	Period
A.13	Safeguards for the Pilot Conditioning Facility	1988 - 1997
A.14	Safeguards for Final Disposal of Nuclear Material in a Geological Repository	1988 - 2002
A.25	Participation in Expert Group Meetings on Safeguards for Final Disposal of Spent Fuel in Geological Repositories	1999 - 2003
A.32	Development of Safeguards for Final Disposal of Spent Fuel in Geological Repositories	2003 - 2006
A.35	Application of Safeguards to Geological Repositories (ASTOR), Group of Experts	2006 - today
A.38	Umbrella Task: Support for Novel Technologies	2006 - today
B.21	Use of Satellite Imagery Data for Geological Repositories Monitoring	2006 - 2011

Besides, the German Support Programme also focused on the safeguards concepts and measures for the dry storage of SF assemblies, which will not be considered in this paper. However, the temporary increase of cask loadings per year due to nuclear power phase-out until 2022 and the long-term interim storage on-site until 2055 or even longer, depending on the start of operation of the future geological repository, are also expected to cause safeguards-related challenges. Please see Ref. [2] for more information.

## 2. German R&D contributions to safeguarding geological repositories since 2010

### 2.1. Disposal concepts

Until 1994, the Atomic Energy Act (AtG) stipulated that the only way for the German energy supply companies to dispose of irradiated fuel assemblies was the reprocessing of SF assemblies. Research on the disposal of waste from reprocessing in boreholes and the disposal of waste containers with spent fuel in horizontal drifts already started in the late seventies. As an alternative to SF reprocessing and disposal of vitrified HLW, the direct disposal of SF was developed further. The feasibility was assessed, the emplacement equipment built and tested, and all safety aspects were evaluated. This led to an amendment of the Atomic Energy Act in 1994 which then allowed the direct disposal of SF without prior reprocessing. After a change of government, reprocessing of SF ceased in June 2005. Today, direct disposal is thus the only way SF can be disposed of in Germany.

In Germany, the reference concept for the disposal of HLW and SF until July 2013 (see 1.1) proposed geological disposal in a rock salt formation. While HLW canisters (mainly canisters with vitrified waste from reprocessing) were to be disposed of in vertical boreholes, SF was to be placed in heavy, self-shielding containers (POLLUX®, weight 65 t) which were to be emplaced in horizontal disposal drifts. For the disposal of spent fuel, an alternative concept – the so-called "BSK 3 concept" – was developed which relies on a vertical borehole emplacement technology. (Note: BSK 3 is the German acronym for fuel rod canister.) As a third option, the feasibility of direct disposal of transport and storage casks – the so-called "DIRECT" concept – was investigated. It offers the possibility to avoid the feasible but quite complex conditioning of the fuel assemblies, thus reducing radiation exposure to the personnel and reducing respective arisings of operational wastes. Studies carried out were very promising and supported that this concept merits further investigations and development work.

In summer 2010, i.e. prior to the 2011 Amendment to the AtG, the German Federal Government launched a preliminary safety analysis to assess whether the salt dome at Gorleben is suitable to host all heat-generating radioactive waste generated by German nuclear power plants. This safety assessment included a repository concept which was optimized to a certain extent during project evolution [3]. The repository design was tailored to the specific geologic environment at the Gorleben

site and served as the main technical basis for the site-specific preliminary safety analysis. This preliminary safety analysis took into account the “Safety Requirements Governing the Final Disposal of Heat-Generating Radioactive Waste” [4] for the very first time.

The study considered two main emplacement strategies for the design approach and the resulting repository (Table II). First, disposal of all heat-generating radioactive waste in self-shielding waste containers in horizontal drifts, and second, disposal of all heat-generating radioactive waste in deep, vertical boreholes. In addition – for comparison only – the emplacement of all heat-generating radioactive waste in transport and storage casks in horizontal boreholes was considered as well.

Table II. Waste streams and waste containers/transport units for the various emplacement variants (modified after [3])

Heat-generating radioactive waste			
Waste stream	Drift emplacement (Variant B1)	Comparative analysis (Variant B2)	Borehole emplacement (Variant C)
Spent fuel elements from PWR, BWR, WWER	POLLUX <sup>®</sup> -10 (fuel rods)	CASTOR <sup>®</sup> (transport and storage casks)	BSK-R <sup>1)</sup> (fuel rods)
waste from reprocessing (CSD-V, CSD-B, CSD-C)	POLLUX <sup>®</sup> -9	CASTOR <sup>®</sup> (transport and storage casks)	BSK-R <sup>1)</sup>
Fuel elements from prototype and research reactors	CASTOR <sup>®</sup> (transport and storage casks)	CASTOR <sup>®</sup> (transport and storage casks)	Modified fuel rod canisters <sup>1)</sup>

<sup>1)</sup> The material is transported underground in re-usable transfer casks.

The designs took into account an updated set of fundamental data regarding the amounts and types of expected heat-generating waste and the documented results of the exploration of the Gorleben salt dome. For both options (emplacement in drifts/emplacement in vertical boreholes), the respective design included a selection of waste containers, the layout of drifts, respectively lined boreholes, a description of emplacement fields, and backfilling and sealing measures. The design results were described and displayed and the differences between the two main concepts were elaborated and discussed. It could be shown that both strategies lead to reliable repository concepts. For the first time in both repository designs the requirement was implemented to retrieve waste canisters during the operational phase, i.e. one main challenge was to show that repository concepts could be developed that meet the new retrievability requirements. Technical approaches how to retrieve emplaced waste containers were developed. It was pointed out that there arises the need to keep transport- and storage casks in adequate numbers and interim storage facilities available until the repository is closed. These approaches will be further evaluated and refined.

## 2.2. Application of radar remote sensing to safeguarding geological repositories

The joint Member State Support Programme (MSSP) task entitled ‘Use of Satellite Imagery Data for Geological Repositories’ was initiated by the need to identify the remote sensing technologies and techniques that will best support the needs of safeguards in monitoring geological repositories. The objective of this joint program was to evaluate the potential effectiveness of various synthetic aperture radar (SAR) earth-observing satellites to detect undeclared activities aimed at diverting spent fuel from a geological repository. The Support Programmes of Finland, Japan, Canada and Germany evaluated various approaches to processing data acquired by the sensors ALOS PALSAR, RADARSAT-2 and TerraSAR-X. An experiment was conducted to evaluate the ability of SAR data to detect specific targets near the underground construction of the Onkalo (Underground Rock Characterisation Facility) in western Finland. Three of the targets were permanent warehouses on the east side of the Onkalo site, the fourth target was a pair of small weather sheds located near a known borehole, one of which was placed next to the existing one on the site as part of the experiment. [5]

Figure 1 shows the results from processing the two TerraSAR-X datasets, acquired in the high resolution spotlight mode in single polarization at 1.1m spatial resolution over the Onkalo site. The datasets were acquired during the placement of the twin sheds (May 23) and after their removal (June 3) with a time difference of 11 days. Figure 1a) displays the first image after co-registration and

applying a 3x3 Kuan filter for reducing the speckle. The location of the three warehouses can be detected, as they are characterised by strong backscatter signals, however, it is not possible to identify the twin sheds at the borehole.

Non-coherent change detection was performed by simply overlaying the two images in a Red-Green-Blue (RGB) colour composite (Figure 1b). The interpretation for the RGB overlay is quite simple: All red- and cyan-coloured pixels indicate changes. Red pixels indicate much higher backscatter intensity on May 23, the cyan ones on June 3. White pixels mark areas with high, black pixels with low backscattering at the two times. Figure 1b) shows a huge number of change pixels. This is mainly due to the forest coverage with varying backscattering in time, and is probably also connected to an inaccurate co-registration.

In coherent change detection, the sample coherence of the repeat pass image pair is commonly used to quantify surface changes related to temporal decorrelation. Temporal decorrelation results from physical surface changes over a specific period of time, due to different weather conditions, changes of soil moisture, vegetation canopy, surface roughness or topography, or man-made changes. Decorrelation effects are demonstrated in Figure 1c). Again, the forest coverage causes temporal decorrelation. The changes due to the installation and removal of the twin sheds cannot be detected.

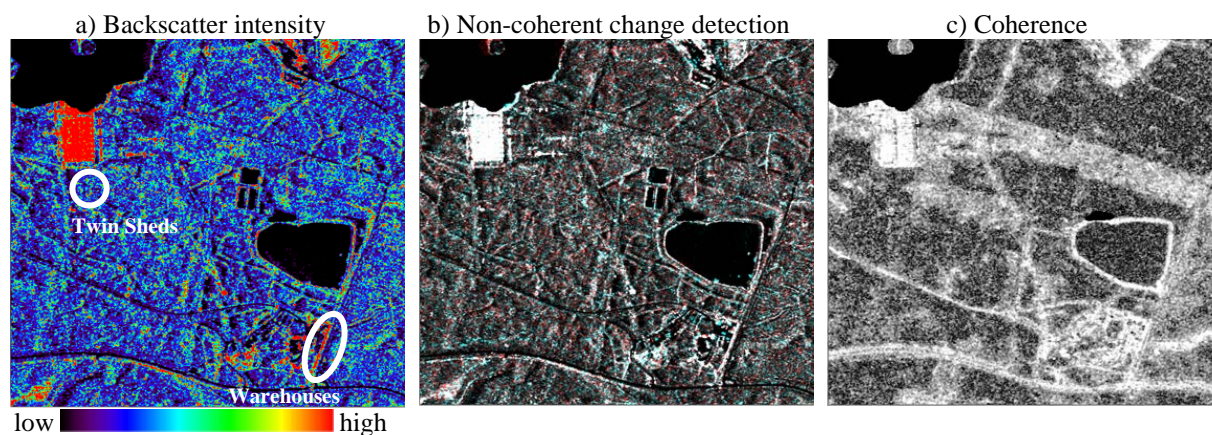


FIG. 1. Results from TerraSAR-X processing. a) TerraSAR-X image acquired at May 23, 2010: Color-coded backscatter intensity. b) Non-coherent change detection May 23 & June 3, 2010. c) Coherence map May 23 & June 3, 2010.

Results from SAR data processing commonly showed that the twin weather sheds were too small to be detected with SAR, particularly amongst the clutter generated by neighbouring trees. Even on a sub-metre optical image acquired by World-View the two sheds were not easily identified. Returns from the three warehouses next to the perimeter fence were detected, but complementary use of other data was required to know that these were warehouses.

The study also demonstrated limitations with SAR depending on the land cover. The predominant boreal forest created strong and inconsistent returns while snow accumulation and its melting were also responsible for big changes in SAR returns. Even in less difficult environments, the geometry of the object with respect to the look direction of the radar will affect the signal strength. However, it should be noted other relevant features were detected, including car park movements, infrastructure changes and changes in excavation material storage areas.

Satellites can monitor what is happening on the surface of a geological repository. They can monitor frequently and see things which may not be apparent to an inspector on the ground. The most useful way of applying satellite imagery to this problem is to look for differences or changes between successive data sets. These changes may be subtle changes in terrain elevation (e.g. spoil heaps or excavation), new features (construction or infrastructure) or changes in returned signal characteristics (e.g. vegetation removal, indicating human activity). Optical imagery may be available during the

summer months, but in the winter, SAR imagery will be available consistently and is capable of detecting safeguards significant features and activities.

### ***2.3. Seismic measurements & modelling***

In the late 1990's, the GER SP began to study the applicability of geophysical measurement methods for the detection of clandestine mining activities and undeclared cavities. But it was only after the end of the 10 years' moratorium at the Gorleben exploratory mine in October 2010 that acoustic and seismic measurements were carried out at Gorleben in 2011/2012, underground at 840 m depth and at the surface. The measurements and evaluations aimed at providing basic knowledge on the detectability of undeclared activities.

During seven weeks of measurements in total nearly all sources of sound and vibration available in the mine were covered, with sensors at several positions and sources at several locations, sometimes with background signals from on-going exploration elsewhere. Geophones, low-frequency accelerometers and microphones as well as piezoelectric high-frequency sensors were used. [6,7]

Seismic signals measured by geophones show excitation to the highest frequency covered, 5 kHz, in many cases of a broad-band character. Periodical working machinery produces harmonic signals in addition. Signals from piezoelectric sensors contain frequencies up to many tens of kHz, they are generally stronger by two to three orders of magnitude than the geophone ones, while the signal-to-noise ratio is similar. Coupling from acoustic waves to seismic vibration is relevant, in particular for heavy vehicles.

A catalogue of sources with their signal strength and their decrease with distance was produced from the geophone measurements that comprised frequencies from about 2 Hz to about 5 kHz. The signal strengths vary by a factor 2 to 5 for similar conditions. Fitted by a power law, the decrease with distance is with an exponent mostly between -2 and -1. The peak-to-peak values of vibration velocity, referred to 100 m distance, range from tenths of micrometres/second for a hand-held chain saw via a few  $\mu\text{m/s}$  for other tools such as picking, to tens of  $\mu\text{m/s}$  for vehicles, big drilling machines, the scaler, the roof cutter and sledge-hammer blows. A grader with plate compactors produces hundreds of  $\mu\text{m/s}$ , and a blast shot around 100,000  $\mu\text{m/s}$ . The last two sources could be detected at the surface, too, at about 1.1 km slant distance; blasts were even seen at 5-6 km distance. Localisation of sources was studied with a linear array of piezoelectric high-frequency sensors. For an impulse-type source the hyperbolic method of using time differences of arrival of P and S waves worked in an adjacent drift with errors of  $\pm 15$  m. Beam forming allowed localisation of pulsed as well as repetitive sources also in more distant drifts, with errors of  $\pm 25$  m.

During the emplacement phase monitoring for undeclared activities by traditional means, such as video cameras, could be complemented by seismic sensors. In order to discriminate against all kinds of activities going on in the repository the spacing would have to be close, for example every 50 m. With closure of the repository such activities will end, and sensors can only be deployed at some distance from it. Monitoring could then use an underground geophone "fence" around the repository, with sensors in the adjoining rock for example 500 m from the salt-dome margin and possibly in the salt 1 km off the repository, plus some in the overburden above the salt dome. With that excavation by drilling and blasting could be detected by a simple amplitude criterion. Excavation by tunnel boring machine or road header machine and other activities would produce much weaker seismic signals. What sensor spacing and detection scheme could be used to detect these needs to be studied in more detail.

Based on the results, a follow-up project was started in 2012, devoted to numerical three-dimensional modelling of signal propagation of seismic waves from different sources in the salt dome to longer distances in the salt dome and, in particular, to the surrounding and overlying sediment. The aim is to investigate what the detection capabilities of seismic sensors in the vicinity of a repository in a salt dome would be. Figure 2 shows a much simplified model of the underground structure used in the first



computations. Exemplary signals at one sensor position from one force pulse and from 100 repeated blows are shown in Figure 3. The evaluations are on-going. [8]

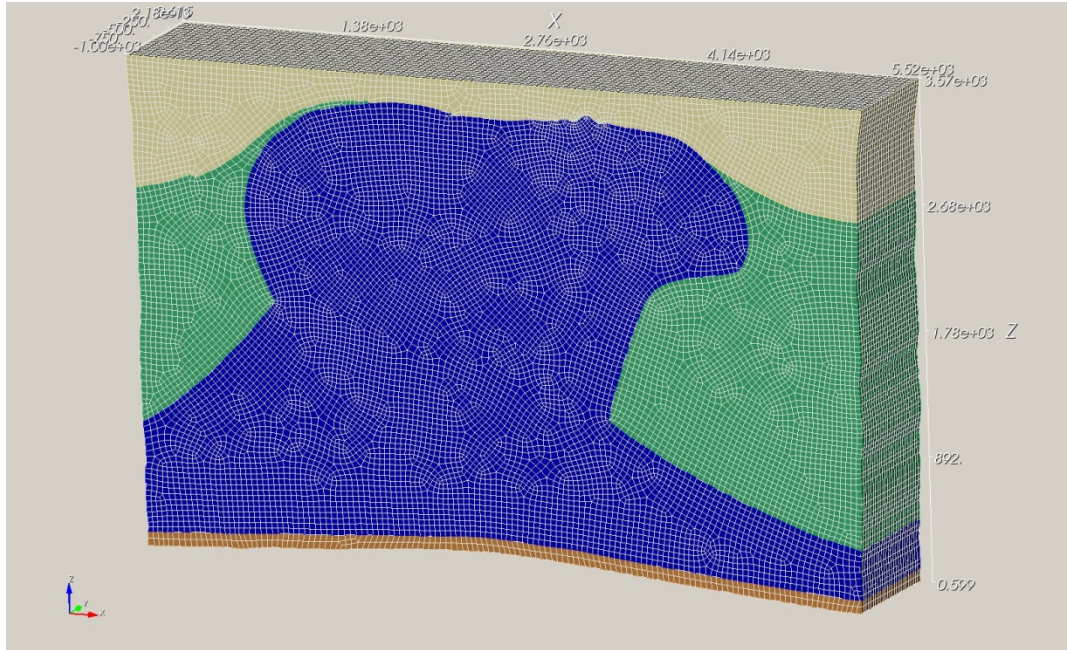


Fig. 2. Strongly simplified model of the salt dome and its surroundings with mesh used in the first computations.

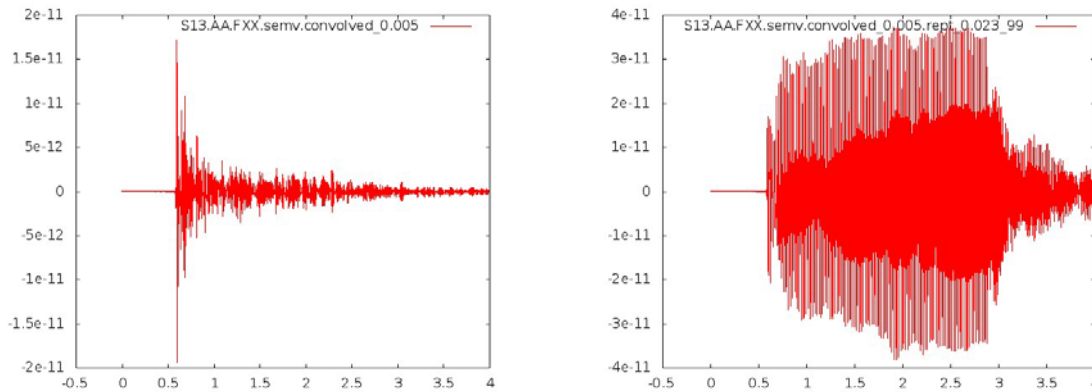


FIG. 3. Exemplary signals from one (left) and 100 consecutive (right) horizontal force pulses with 23 ms spacing (simulating a pick hammer). Shown is the horizontal seismic velocity in x direction (see Figure 2 in m/s versus the time in s, for a fictitious time-integrated force amplitude of 1 N of half duration 0.41 ms. Source in salt-dome centre at 900 m depth, sensor in 2544 m distance, just beyond the dome margin, at the same depth.

## 2.4. Directive underground radar

A feasibility study under the German Support Programme has investigated the applicability of directive underground radar for monitoring geological repositories. Radar monitoring in the context of safeguards is aimed at detecting and localizing unauthorized underground mining activities in an early stage and in a sufficient distance [9].

Radar monitoring as part of geotechnical engineering is restricted to few applications so far, mainly in form of repetitive linear measurements. Repetitive surveys out of boreholes or drifts involve some drawbacks concerning safeguards requirements, such as high maintenance and positioning inaccuracies. In this study a static radar system has been selected to omit these disadvantages.

Directive radar antennas provide the direction of activities. A monitoring system consisting of an array of directed static radar probes could probably be realized as a highly accurate, durable and low-maintenance automatic early warning system. The radar system could form a kind of protective shield around a repository to detect and localize possible activities in an early stage and in a sufficient distance. However, the applicability of the radar method is restricted to locations with low conductive conditions like in dry rock salt and in some crystalline formations.

The given feasibility study considers the following unauthorized activities: drillings, cavern leaching, hydraulic fracturing, explosions, and heading techniques. All activities are related to drillings at least, so the question is whether a small diameter drill hole could be detected and separated from known mine work. Accordingly, the detectability of possible access types with different materials, sizes and geometries has been investigated. It has been shown that the detectability not only highly depends on the electrical properties of the object, but also on the geometrical position between object and radar antenna. The lowest detectability was estimated when the activity axis lies diagonally to the radiation path of the radar signal. In another step 2D-finite difference simulations were carried out to examine the influence of the geological environment and mining activities on the detectability of a possible unauthorized access (Figure 4). As a basis a section of the Gorleben salt dome was used. The investigations showed so far, that the expected signals of small size unauthorized activities could be very low. But modelling has demonstrated that under low conductive conditions also low amplitude signals could be detected up to several hundreds of metres from the antenna.

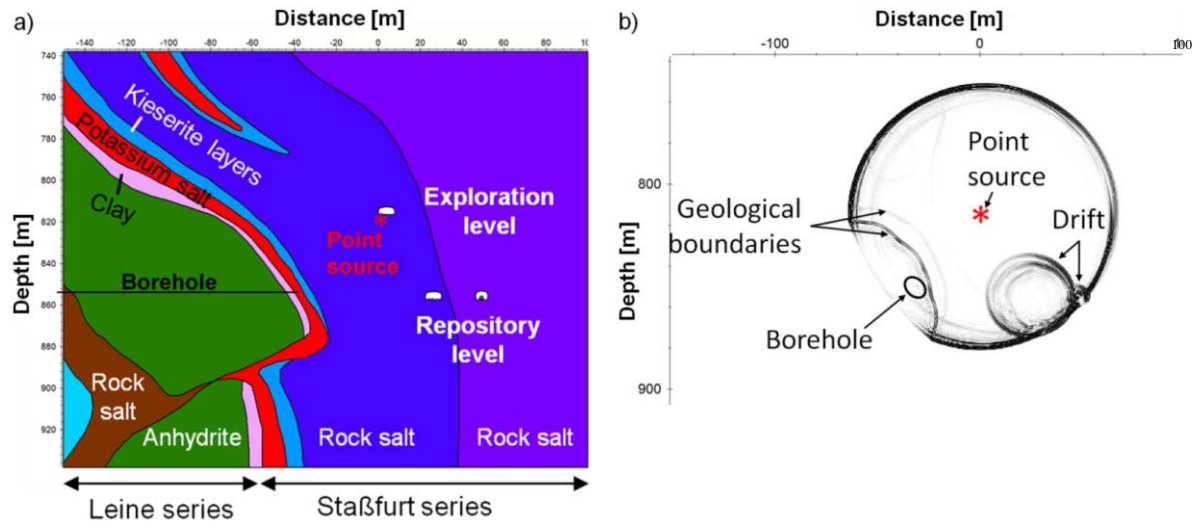


FIG. 4. 2D finite difference simulations. a) Model of a section of the Gorleben salt dome used for the simulations. A horizontal borehole with diameter of 0.125 m approaches the potassium salt in a depth of about 856 m. b) Simulated wave field of the model in a) at a travel time of 536 ns.

The behaviour of radar is highly dependent on the local electromagnetic properties. The applicability of the radar method is restricted to locations with low conductive conditions like in dry rock salt and in some crystalline formations. Location-specific information should contribute to the final decisions of a radar system at a location. Range and resolution of the radar system are defined by the measuring frequency. In this study also the meaning of the measuring frequency and the influence of the local electromagnetic properties has been investigated.

To detect possible activities in an early stage and in a sufficient distance, the monitoring system has to be high sensitive. To improve the sensitivity even in greater distances the static radar system could be optimized in comparison to mobile radar systems. The optimization includes directive antennas, the use of several measuring frequencies, long time data acquisition and redundant design. The layout of the radar system must be integrated into the repository concept.



The task of a radar monitoring system is to detect a low amplitude signal and to separate it from mine workings, geological conditions and technical and geological noise. Additionally every activity in the mine drifts changes the data. So the challenge of a monitoring system is not only to detect a signal but also to separate known mine workings from unauthorized activities.

## ***2.5. Autonomous navigation and localisation***

Through the use of inertial sensors - usually mounted on or in the shoe – it is possible to determine the location of people in indoor or underground areas, where satellite-based positions systems or WiFi points may not be available. Hereby one usually requires a map of respective indoor or underground areas, such as buildings or underground mines. Using the FootSLAM algorithm developed by DLR one can “learn” a suitable map when persons, equipped with foot-mounted inertial sensors, walk in a building, and visit regions repeatedly. The processing algorithm uses machine learning techniques based on Bayesian inference.

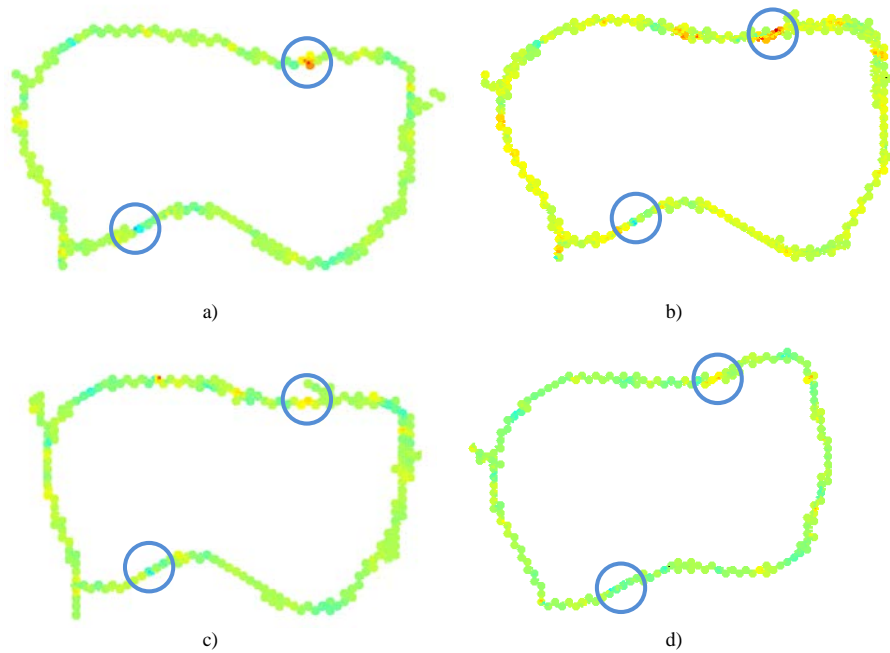
In the end of 2013 a measurement campaign was carried out in the graphite mine Kropfmühl situated in Hauzenberg close to Passau. The main goal of these measurements was to prove that for demanding scenarios such as a mine, it is possible to get a reliable positioning by using inertial sensors with the aid of magnetometers and barometers. The campaign was carried in the visitors’ mine which was down to 40 m and in the active mine which was down to 200 m. This visit took about 3.5 hours.

The main intention of the experiment was to measure the magnetic field intensity and implicitly the feasibility of FootSLAM/MagSLAM in difficult environments. The experiments focused especially on the magnetic field, because the magnetic field provides a signature of the local environment that can be used for accurate localization and mapping. Due to disturbances the magnetic field varies in the presence of ferromagnetic materials and these variations can be used as magnetic signatures. Two data components of the recorded data were taken into account for the experiments: the odometry (human step measurements) for FootSLAM and the local magnetic field intensity for MagSLAM. SLAM (Simultaneous Localization and Mapping) implies mapping of the environment parallel to localization. FootSLAM uses a hexagonal raster in 2D and hexagonal prisms for 3D dimensions as basis for the map [10, 11]. For MagSLAM, the FootSLAM map is extended by a hierarchy of magnetic field bins with differently sized hexagon cells. The magnetic field is modeled to be a scalar random variable following a Gaussian distribution with unknown mean and variance. The FootSLAM approach – actually a simple Sequential Monte-Carlo (particle filter) approximation to the Bayesian estimator – can be mathematically extended to handle the MagSLAM problem [12].

The results for applying the FootSLAM and MagSLAM algorithms within the visitors mine for four pedestrian walks are presented in Figure 5. One loop within the visitors mine was about 250m. Due to some restrictions like sensor loosening due to the wet environment, the number of loops differed for the four walks: 1.5 loops for walk-1 (Figure 5 a), 3 loops for walk-2 (Figure 5 b), 4 loops for walk-3 (Figure 5 c) and 1.25 loops for walk-4 (Figure 5 d). In the experiments, a combination of FootSLAM and MagSLAM was used. In Figure 5, the color encodes the sample mean magnetic field intensities of the maximum likelihood particle at the end of the walk, where red encodes higher intensity. Distinctive magnetic field characteristics are encircled in blue. The magnetic fields show that, although the sensor fell down for two pedestrians after 1 loop (walk-1 and walk-4), the map of the visitors mine is reconstructed very well. The shape of these maps is close to the shape of the other walks. Overall, the long 250 m walks were recorded successfully even in the case of only one loop within the visitors mine. It should be noted that FootSLAM/MagSLAM maps are rotation invariant and that the FootSLAM converges to a map more precisely, when there are loop closures.

The magnetic intensities encircled indicate that the same behavior for all walks exists: high intensity within the upper circle and low intensity within the lower circle. This suggests that the mine could have a specific magnetic signature. In addition, the results from applying MagSLAM within the active mine show similar behavior: The magnetic signature is very similar for all walks, indicating that the

magnetic signatures have a common basis dependent on the position. Therefore, it may be possible to use the magnetic signature for verification, change detection, and also positioning.



*FIG. 5. A two layer hierarchical magnetic field map composed of regular hexagonal grids for walk 1 (a) - 4(d). Distinctive magnetic field characteristics are encircled. The color encodes the sample mean magnetic field intensities of the maximum likelihood particle at the end of the walk, where red encodes higher intensity.*

In addition to the visual comparison described above, the magnetic field over the distance travelled was compared. Due to the fact that persons have their own speed, the magnetic field is not comparable over time, however, if the magnetic field concerning the distance travelled is considered, a comparison of the four walks becomes possible. Since the measurements were very accurate with regard to the distance travelled, a cross covariance function could be applied to the magnetic intensity over distance. As the distances are not equally distributed, an approximation to the measurements was required first in order to obtain magnetic intensity values over equally distributed distances. For this reason, the magnetic intensity values were interpolated by applying a linear algorithm. With this, it was possible to apply a cross covariance function in order to see if the magnetic intensity measurements of two pedestrians match.

To obtain a measure of similarity, the normalized cross-covariance between the walks was computed. Since position and time vary for the four walks, a sliding window of size 20 meters was applied in order to compute the normalized cross covariance functions of these windows. The results for the normalized cross covariance function of the sliding windows of walk-1 and walk-2 are given in Figure 6a). The figures shows that there are maxima for several window starting points and that the cross covariance is significant at these locations. For some of the windows the normalized cross covariance is less high. There are many reasons for it: the two pedestrians did not walk exactly the same way with the same velocity at the same time. And they did not walk in the same order – thus positions can be changed. Figure 6b) shows an example for the normalized cross covariance of the window starting at 158 m, where a peak of the magnetic field intensity is observable close to zero confirming high correlation. From the applied set of normalized correlation functions several windows show a comparable high correlation.

The results confirm that the measured magnetic fields have a common basis dependent on the position for all four pedestrians walking the similar route and that the magnetic field intensity can be used for pedestrian navigation. It should be noted that the four test persons did not walk an identical route – every walk differed slightly as each person walked differently, i.e. on the left of the metallic railway,

or in the middle or on the right. Even in the tunnels without metallic railways, the test persons did not take an identical path. Therefore, the magnetic field intensity differs a little bit. But the overall characteristics of the magnetic field intensity plotted over the travelled distance shows that it is possible to obtain a magnetic signature, which may be used for verification, change detection and positioning.

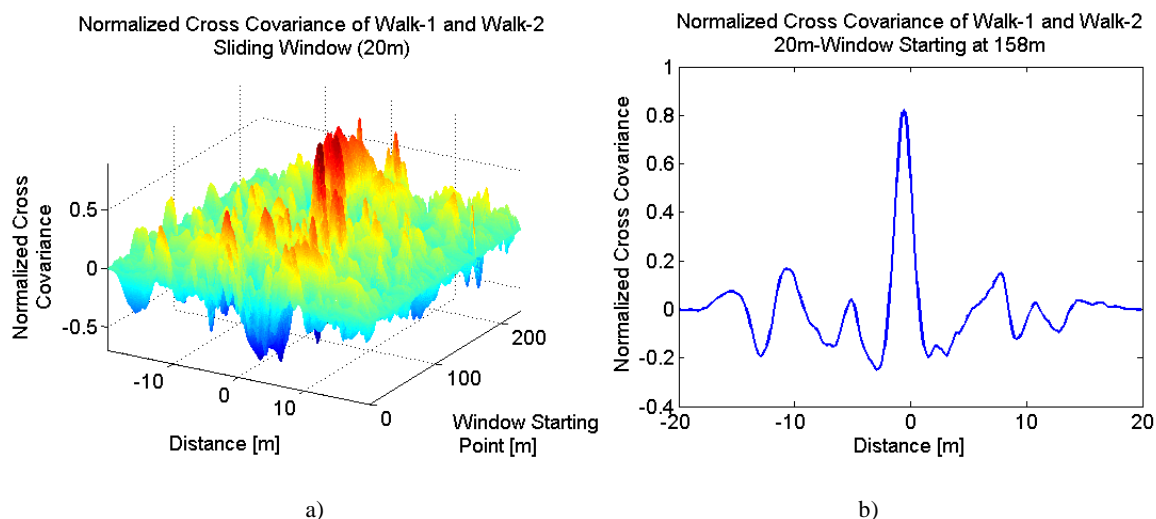


FIG. 6. The normalized cross covariance of the magnetic field intensity of walk 1 and 2 for a sliding window of size 20m (a) and for the window starting at 158m (b).

### 3. Lessons learnt

The studies related to geological repository safeguards identified the following issues to be of essential relevance:

- Retrieval of spent nuclear fuel during the operational phase and in the post-closure phase;
- Capability to verify and re-examine the underground structure and, thus, the design of the repository (Design Information Verification and Re-examination);
- Applicability of geophysical measurement methods for the detection of clandestine mining activities and undeclared cavities;
- Applicability of satellite imagery for monitoring the site during its lifespan (pre-operational, operational and post-closure phases);
- Definition of the physical boundaries of an underground repository for materials under IAEA Safeguards.

The studies carried out also highlighted the benefits from international cooperation on topics of mutual interest. International cooperation in research and development is essential to facilitate development of concepts as well as equipment and (novel) technologies for safeguarding geological repositories and encapsulation plants. International cooperation offers opportunities to exchange views and experiences on all relevant activities in the design, implementation (and operation) of geological repositories and encapsulation plants.

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